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13. ABSTRACT (Maximum 200 words)

The reliability of composite materials when exposed to multiple degradation environments was characterized. First, a new procedure based on inverse analysis and experimental measurements was established to characterize the transient moisture diffusion process in composites as a function of relative humidity and temperature. This procedure accounted for the heterogeneous microstructure in considerable detail, and was utilized to obtain the diffusivity and the maximum moisture content of the epoxy phase, and to determine stress distributions in the composite. In addition, high-grade composite laminates were exposed to various environmental conditions to characterize synergistic mechanisms of degradation. It was observed that the environmental factors such as UV radiation and condensation act synergistically to produce extensive material degradation. Mechanical testing was employed to determine the effects of such degradation on properties such as modulus, strength, and residual modulus under fatigue. Finally, a new technique based on optical fiber sensors was designed to detect and quantify embedded delamination and damage states via smart post-processing of measured data. This task required formulation of various inverse methods to process data to quantify unknown parameters. The results from this research have been made available to the composites community via numerous publications and presentations.

14. SUBJECT TERMS Reliability of Composites, Carbon Fiber Reinforced Epoxy Matrix, Residual Strength, Fracture, Hygrothermal and Ultra-Violet Degradation, Transient Moisture Absorption, Inverse Analysis.	15. NUMBER OF PAGES 15
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FINAL PROGRESS REPORT

Ultra-Reliability Evaluation based on Multi-Property Degradation Mechanisms

ARO funded project 2000 – 2002

Foreword

Various aspects of multiple property degradation of fiber-reinforced composites were investigated under the funding of the U.S. Army Research Office. The current project enabled development of novel experimental and interpretation procedures and quantify the degradation mechanisms of next generation composites. The support of ARO is gratefully acknowledged.

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Project Objectives

Material induced failures often initiate from multiple degradation mechanisms. In order to assess the reliability, it is important to understand and quantify the synergistic interactions between various damage modes occurring across the material length scales. In order to determine the reliability, novel approaches to quantify the damage accumulation and residual strength are required. The main objective of this research project is to develop an integrated system composed of a non-traditional diagnostic/sensor technology for the real-time sensing of materials and innovative computational data-processing schemes for the degradation extraction/evaluation. Specifically, graphite/epoxy and thermoplastic resin composites under various environmental and thermo-mechanical conditions are evaluated. In these complex material systems, it is difficult to make direct measurements of the multiple parameters necessary to quantify damage and residual strength. In such systems, defined by complex internal micro-structures, the only way to determine or estimate the parameters is through *indirect* measurements of response variables. Typically, measurements must be made on the surface of a specimen while the needed parameters are related to embedded physical phenomena associated with the internal microstructure of the material. Thus new data-processing procedure based on inverse analysis techniques that enable the critical unknown material parameters to be determined from the time-history or load evolution of measurable quantities are needed.

In evaluating degradation mechanisms, it is important to establish physico-chemical based models which capture the spatial and temporal evolution of various damages. Material degradation due to phenomena such as hygro-thermal polymer plasticization, UV radiation leads to physical flaws such as micro-cracks which accelerate the degradation mechanisms due to increased surface area and void volume. Such coupled behaviors cause an inherent randomness

to such processes. In this program, the statistical nature of failure condition will be carefully taken into account in the modeling of residual strength and remaining life of composites.

Summary of Results

Transient Moisture Diffusion through Composites: Inverse Technique and Internal Stress Analysis

A new procedure based on inverse analysis and simple weight measurements is presented to estimate critical moisture diffusion parameters of composite (Vaddadi et al, (2000A)). The procedure was tested with actual high-grade carbon-epoxy composite specimens placed in a controlled environmental chamber. Using the measured relative weight gain as input, the inverse analysis technique was utilized to obtain *best estimates* of the diffusivity and the maximum moisture content of the epoxy phase. The inverse analysis uses Kalman filter, which is well suited for estimating unknown state parameters under non-linear transient conditions. In order to reference the measured weight gain with the diffusion parameters, a detailed finite element model was constructed. The half-thickness composite model contained well over 1000 individual fibers, and they were distributed randomly so that it captured the key geometrical feature of real composites, as illustrated in Fig 1. From the comparison study with a simpler model (i.e., hexagonal model) and analytical approximation, we found that modeling of many randomly distributed fibers was critical for obtaining accurate estimates of moisture diffusion parameters.

Our study also quantifies the differences in transient moisture absorption between the heterogeneous model and the analytical model with effective properties, as shown in Fig 3. Large differences indicate that the determination of each constituent's diffusion parameters is critical. Instead of determining the diffusivity and maximum moisture content of epoxy already in the composite, one may opt to seek these parameters for bulk epoxy. However, in many instances, the same particular epoxy is not available in bulk form, and the curing process used for composites may not produce same diffusion properties for epoxy. Furthermore, the present procedure also allows for the testing of aged composites to determine their moisture transport characteristics.

In general, to achieve good convergence characteristics in the inverse analysis, measurement of more than one single parameter is needed. However, to keep the experiment simple and to avoid additional measurements for the moisture absorption, a potential convergence problem was overcome by supplying the weight gain measurement at many time increments (i.e., every 24 hours) in the present inverse analysis. Although true values of the unknown parameters cannot be verified in any inverse analyses, the best estimates for the diffusivity and the maximum moisture content obtained here showed high degree of accuracy. The simulated results, using the best estimates, as input produced extremely good correlation with the experimentally measured record. The utilization of inverse analysis allows not only the effective use of the experimental measurements but also shortens the measurement duration drastically. Our results also show that good estimates can be obtained with a fraction of time needed to reach full moisture saturation of the composite. This feature is particularly attractive for testing at lower temperatures when saturation may take several months if not years.

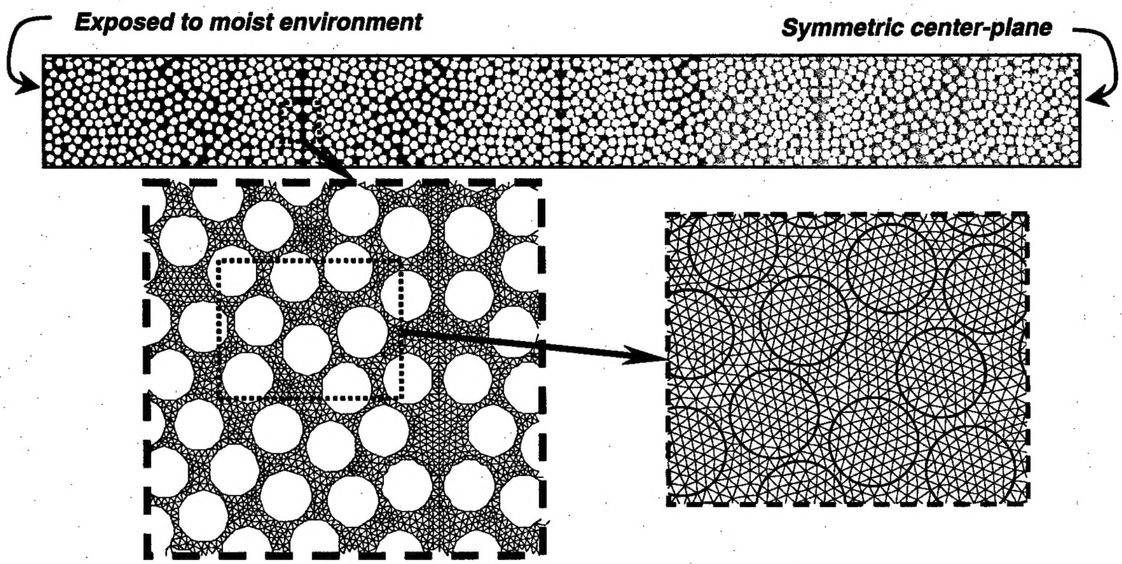

Fig. 1. Shades of transient moisture distribution through epoxy matrix after 288 hr exposure to R_H = 85% and T = 85°C environment. A small region of finite element mesh used in the transient analysis is also illustrated.

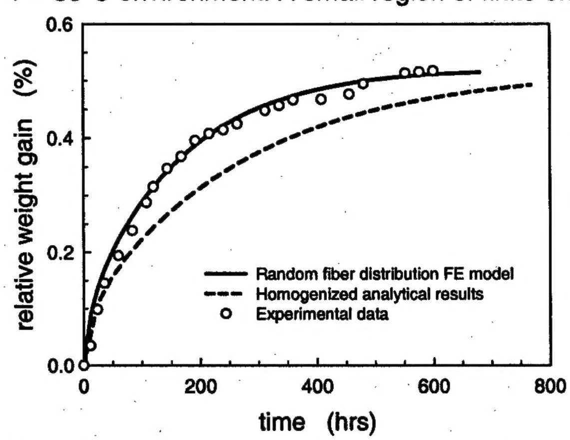

Fig. 2. Comparison of experimental data with random and regular fiber models and analytical

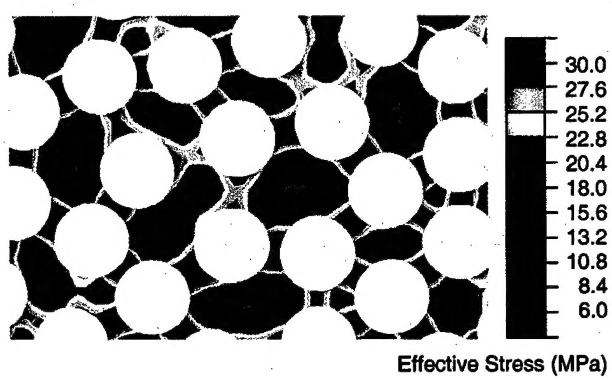

Fig. 3. Contours of von Mises effective stress in epoxy due to transient moisture transport.

The required steps in the proposed procedure to measure the diffusivity and the maximum moisture content are summarized below.

1. Carry out moisture absorption test for specific environmental conditions and measure the weight gain periodically (e.g., every 24 hours).
2. Perform preliminary finite element analysis and compare the results with the experimental record to ensure the selected domain of unknown parameters is appropriate.
3. Establish reference data for the inverse analysis by generating the weight gains for various sets of state parameters (C^*, D). Use cubic Lagrangian functions to interpolate the relative weight gain and its gradient with respect to the state parameters.
4. Prescribe suitable values for co-variant matrices P_0 and R_t.
5. Carry out the Kalman filter process for various sets of initial estimates for C^* and D. Create intensity of convergence plots to determine the best estimates.

A separate study from the coupled stress-moisture flow analysis revealed high stress concentration near regions of fiber clustering during moisture absorption (Vaddadi et al, (2000B)). As shown in Fig 3, the magnitudes of stresses can reach significant level and these regions would be susceptible to damage initiation. Although residual stresses generated during manufacturing as well as the mismatch in the coefficients of thermal expansion were not accounted in the present study, these effects will be included in a future analysis.

Synergistic Degradation of Composites by UV Radiation and Condensation

The degradation of an IM7/997 carbon fiber reinforced epoxy exposed to ultraviolet radiation and/or condensation has been characterized. Based on observations of physical and chemical degradation it has been established that these environments operate in a synergistic manner that causes extensive erosion of the epoxy matrix (Kumar et al, (2000A)).

In order to study degradation mechanisms resulting from UV radiation and water condensation, specimens machined from $[0]_8$, $[90]_8$ and $[0/90]_{2S}$ laminates of IM7/997 carbon-fiber/epoxy composite were subjected to various exposure conditions in a QUV/Se weathering chamber (Q-Panel Lab Products, Cleveland, Ohio). The QUV/Se reproduces damage caused by sunlight, rain and dew by exposing materials to automated cycles of UV radiation and water vapor condensation. Several specimens of each of the three laminate configurations were subjected to the four different exposure conditions:

A. Exposure to Only UV Radiation: For this case, specimens were exposed to UV radiation in the 295-365 nm band at a temperature of 60°C. An irradiance level of 0.68 W/m^2 at 340 nm was chosen to match the typical maximum irradiance of summer sunlight at noon. The elevated temperature, selected to accelerate the degradation process, was small as compared to the glass transition temperature of epoxy ($T_g \sim 210$ °C).
B. Exposure to Only Condensation: In this exposure condition, the specimens were exposed to water vapor condensation at 50°C. Condensation on the specimen surface was achieved by water evaporation and resulted in 100% relative humidity inside the testing chamber. This condition simulates dew and rainfall, and results in both cyclic washing away of the specimen surface and in moisture absorption by Fickian diffusion through the epoxy matrix. As for the case of UV radiation exposure, the temperature was elevated slightly to accelerate the degradation process but not affect the basic mechanisms.
C. Sequential Exposure to UV Radiation followed by Condensation: In this exposure condition, the specimens were first exposed to only UV radiation followed by exposure to only condensation. The conditions for either exposure were the same as for the two independent exposure tests discussed above.
D. Cyclic Exposure to both UV Radiation and Condensation: In the final exposure condition, the specimens were exposed to alternating cycles consisting of 6 hours of UV radiation followed by 6 hours of condensation, the exposure conditions being the same as for single environment tests, as outlined above for exposure conditions A and B.

Physical degradation mechanisms resulting from different environmental exposures were monitored by weight loss and/or gain, and by micrographic observations of the composite surface. Figure 5 plots the variation of specimen weight as a function of time, for specimens subjected to the four degradation conditions. Specimens exposed to 500 hours of only UV radiation exhibited a minor 0.27% decrease in weight, which was attributed to the expulsion of

volatiles and residual moisture. On the other hand, specimens that were subjected to only water vapor condensation gained weight, and demonstrated a typical of time-dependent Fickian diffusion behavior. These specimens gained 0.89% by weight and approached complete saturation after 500 hours of exposure to condensation. When specimens were exposed sequentially to UV radiation followed by condensation, the results were as expected from the observations made for individual exposure conditions. The specimens initially lost weight during the UV radiation cycle and subsequently gained weight during the condensation cycle, and the actual change in weight was a simple time-shifted linear superposition of results obtained for individual exposure conditions. However, when the specimens were cyclically exposed to both UV radiation and condensation, the change in specimen weight was completely unexpected.

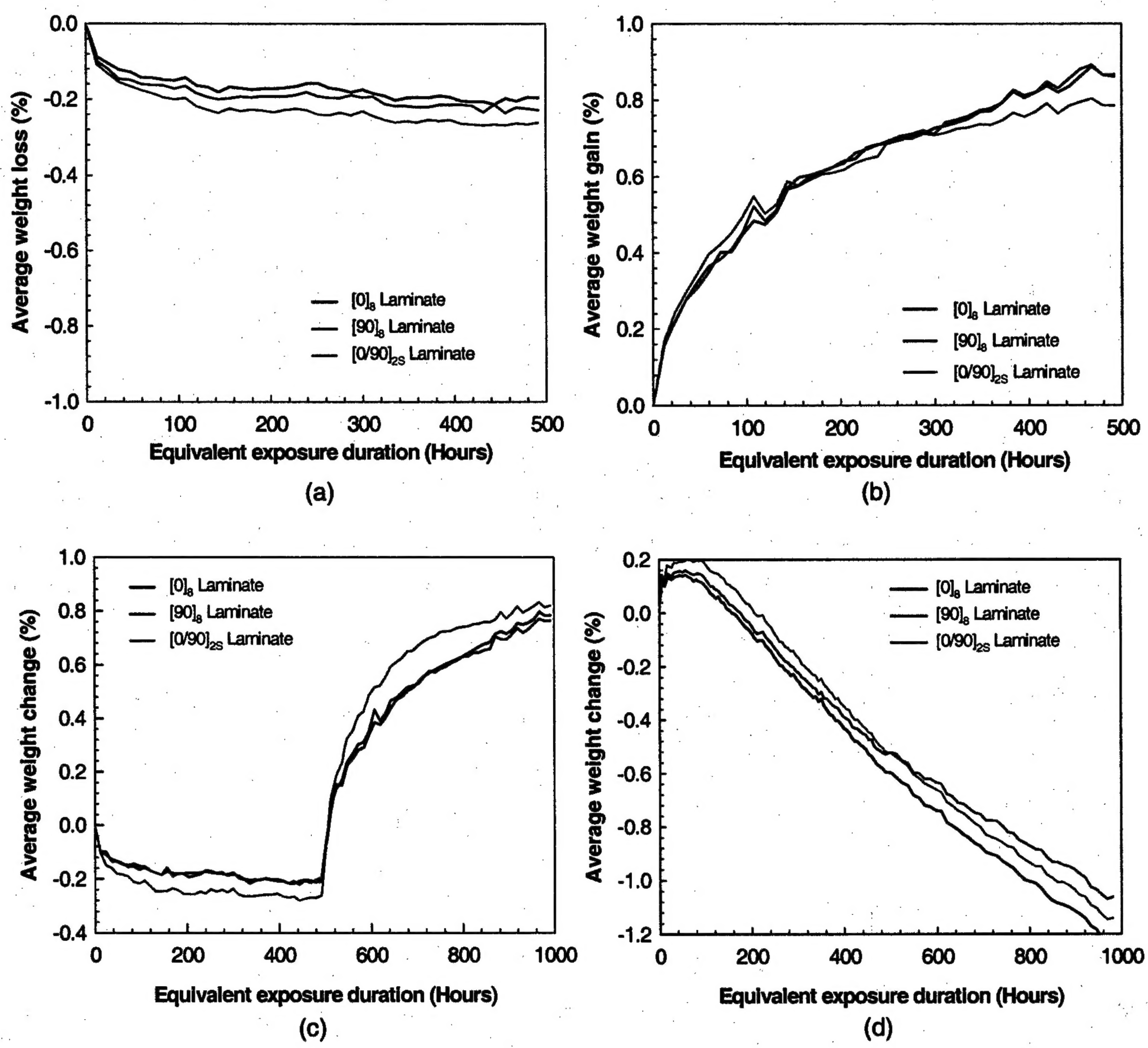

Fig. 5. Change in specimen weight, as a function of time: (a) Exposure to only UV radiation, (b) exposure to only condensation, (c) sequential exposure to UV radiation and condensation, and (d) cyclic exposure to UV radiation and condensation.

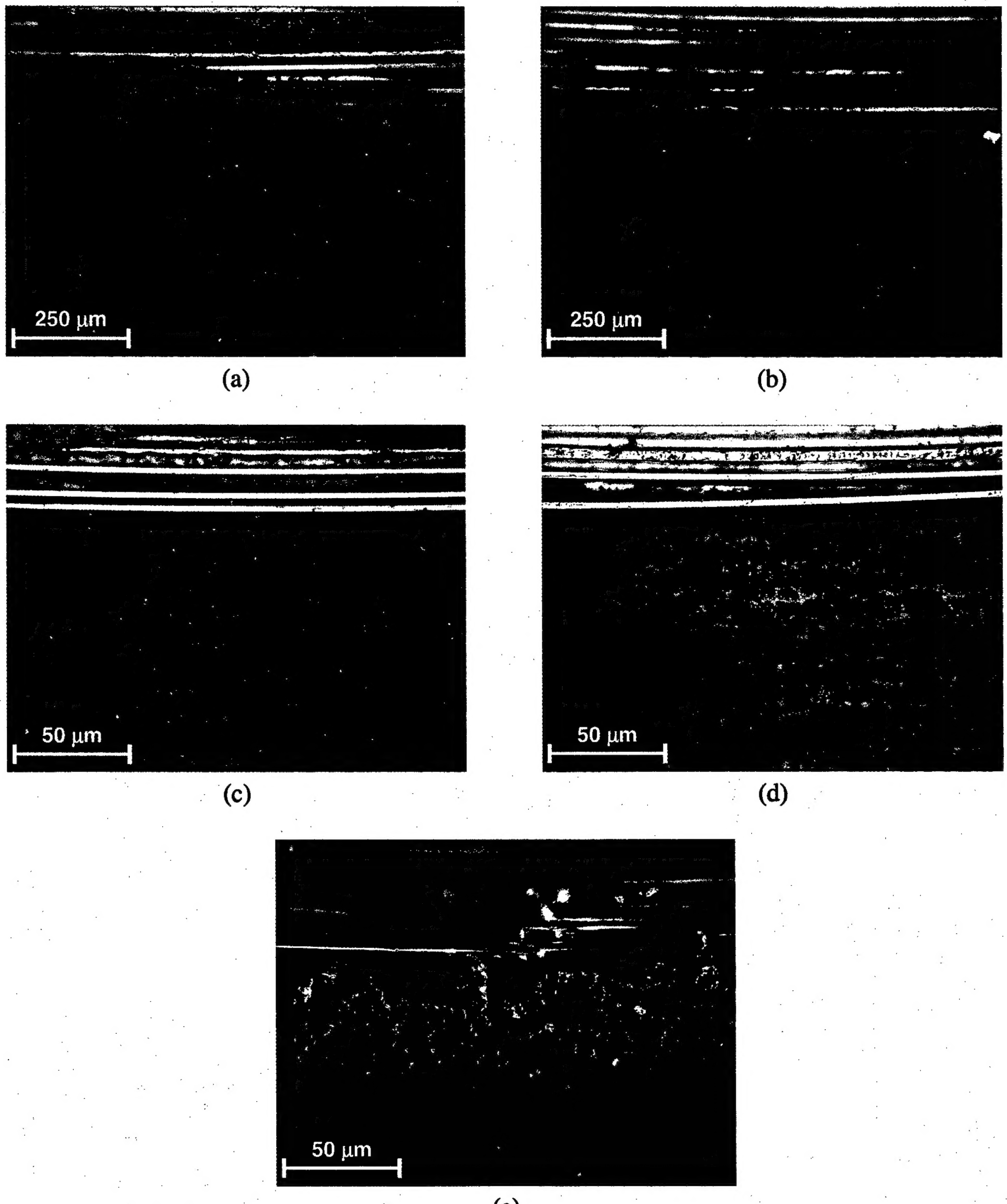

Fig. 6. Optical micrographs for the edge of $[0/90]_{2S}$ specimens: (a) undegraded, (b) exposed to only UV radiation, (c) exposed to only condensation, (d) sequentially exposed to UV radiation followed by condensation, and (e) cyclically exposed to UV radiation and condensation.

These specimens exhibited continuous weight loss at a steady rate throughout the exposure duration, which indicated that material was being removed from the composite specimens. Based on micrographic observations and FTIR analysis it was determined that UV radiation and condensation operate in a synergistic manner that leads to extensive matrix erosion, matrix microcracking, fiber debonding, fiber loss and void formation.

Figure 6 illustrates degradation by the four different environmental conditions by providing a direct comparison of the images of $[0/90]_{2S}$ cross-ply specimens exposed to various environments. This series of images demonstrates that severe erosion of the epoxy matrix due to synergistic effects of UV radiation and condensation will lead to loss of structural integrity in laminated composite structures. Exposure to UV radiation results in the formation of a thin surface layer of chemically modified epoxy. Subsequent water condensation leaches away soluble degradation products, which exposes a fresh layer that can once again be attacked by UV radiation. In this manner, a repetitive process is established that leads to significant erosion of the epoxy matrix. Furthermore, it is also conceivable that the presence of absorbed water molecules in the epoxy matrix can enhance the photo-oxidation reactions due to increased availability of OH^- and H^+ ions. The matrix erosion process has a significantly adverse effect on the integrity of the epoxy-rich inter-ply region in composite laminates.

Residual Strength after Degradation Upon Exposure to UV Radiation and Condensation

Uniaxial tension testing was conducted to determine the effects of degradation by UV radiation and condensation on the deterioration of mechanical properties. Various specimen configurations were tested to determine the longitudinal and transverse moduli, E_L and E_T, the Poisson's ratio, ν_{LT}, the ultimate longitudinal tensile strength, F_L^{ut}, and the transverse tensile strength, F_T^{ut}. The specimens were subjected to uniaxial loading in tension on a servo-hydraulic universal testing machine in displacement-controlled mode with crosshead displacement rate of 0.381 mm/min. The ends of the specimens were untabbed and held in wedge grips with 100-grit sandpaper. Longitudinal elastic properties, E_L and ν_{LT}, were determined from tests conducted on $[0]_8$ specimens, while transverse elastic properties, E_T and ν_{TL}, were determined from $[90]_8$ specimens. The longitudinal tensile strength, F_L^{ut}, was determined based on the uniaxial tensile strength of cross-ply specimens, F^{ut}, while the transverse tensile strength, F_T^{ut}, was determined based on the failure load observed for the $[90]_8$ specimens .

Figure 7 plots the variation of the longitudinal tensile modulus, E_L, for specimens exposed to various combinations of UV radiation and/or only condensation. No appreciable change in E_L was observed for any of the exposure conditions *A*, *B*, *C*, or *D*. This result was as expected, since, neither UV radiation nor condensation lead to degradation of the carbon fiber. Thus, fiber dominated properties, such as E_L, are not expected to change.

A variation of the transverse modulus, E_T, is plotted in Fig. 8 as a function of exposure to various combinations of UV radiation and/or only condensation. A decrease of 4.2% in the transverse modulus, E_T, was observed for specimens exposed to 500 hours only UV radiation. This decrease indicates that the molecular weight of the epoxy matrix was reduced due to chain-scission reactions induced by photo-oxidation from UV radiation. The small amount of actual decrease in the value of E_T is due to the fact that changes induces by UV radiation are a surface phenomena, while E_T represents a bulk material property. A small, but measurable, decrease of

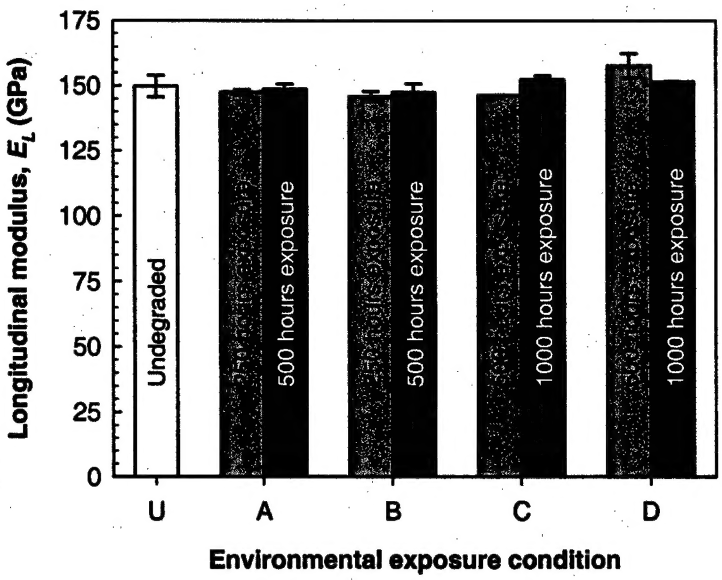

Fig. 7. Variation of longitudinal modulus, E_L, for exposure to UV radiation and/or condensation: *U* – undegraded with no exposure, A – exposure to only UV radiation, *B* – exposure to only condensation, *C* – sequential exposure, and *D* – cyclic exposure.

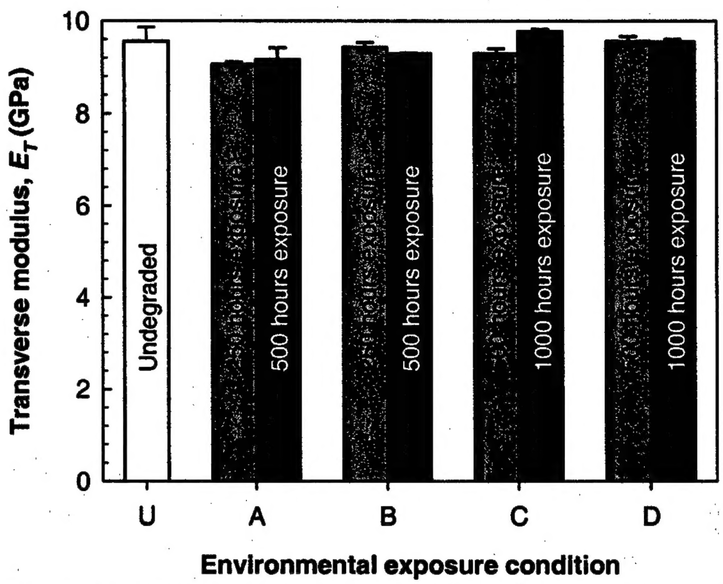

Fig. 8. Variation of transverse modulus, E_T, for exposure to UV radiation and/or condensation: *U* – undegraded with no exposure, A – exposure to only UV radiation, *B* – exposure to only condensation, *C* – sequential exposure, and *D* – cyclic exposure.

2.8% in the transverse modulus was also observed for specimens exposed to 500 hours of only condensation. This decrease in E_T after exposure to condensation indicates that the epoxy matrix underwent hydrolysis and irreversible plasticization. However, no trend could be established for specimens exposed to both UV radiation and condensation, either sequentially or cyclically. The measured values of the transverse modulus, E_T, for either of these two exposure conditions, were

the same as those for the undegraded specimens not exposed to any environment. This indicates that there are some synergistic effects that govern the changes in matrix properties when the specimens are exposed to a combination of both UV radiation and condensation.

Figure 9 plots the variation of the longitudinal tensile strength, F_L^{ut}, for specimens

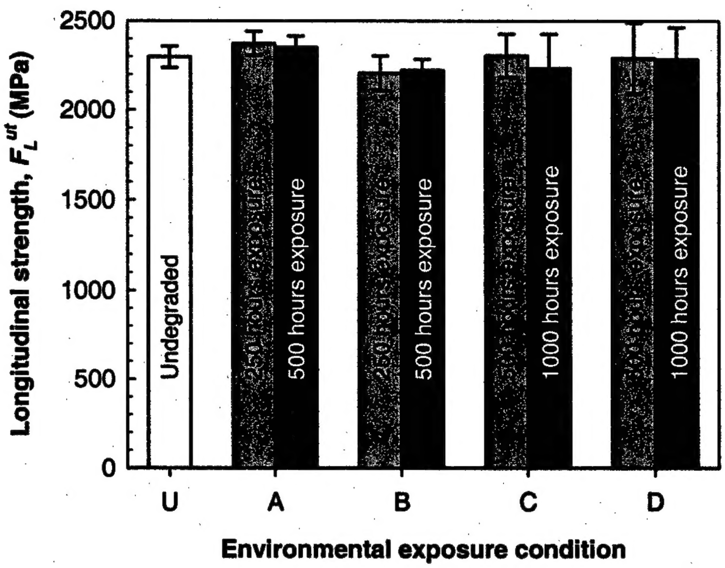

Fig. 9. Variation of longitudinal tensile strength, F_L^{ut}, for exposure to UV radiation and/or condensation: *U* – undegraded with no exposure, A – exposure to only UV radiation, *B* – exposure to only condensation, *C* – sequential exposure, and *D* – cyclic exposure.

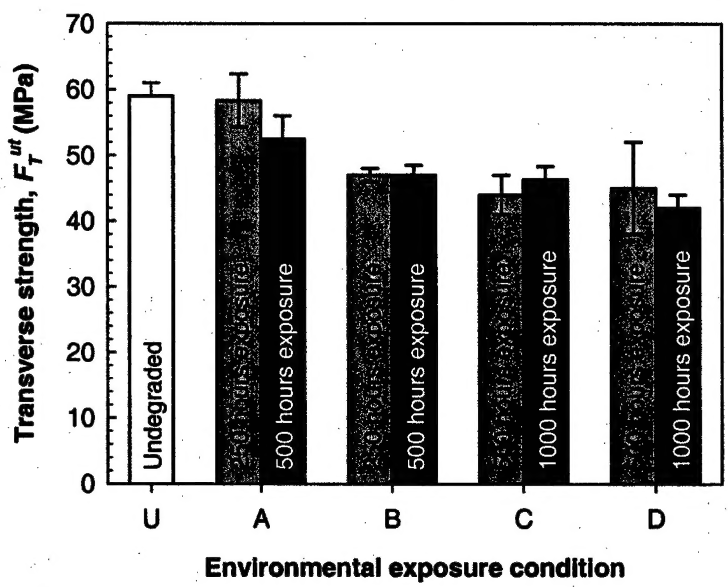

Figure 10. Variation of transverse tensile strength, F_T^{ut}, for exposure to UV radiation and/or condensation: *U* – undegraded with no exposure, A – exposure to only UV radiation, *B* – exposure to only condensation, *C* – sequential exposure, and *D* – cyclic exposure.

exposed to various combinations of UV radiation and/or only condensation. No appreciable changes in F_L^{ut} were observed for any of the exposure conditions *A*, *B*, *C*, or *D*. The longitudinal tensile strength is a fiber-dominated property. Since the carbon fibers themselves are not affected by either UV radiation or condensation, F_L^{ut} is not expected to change.

The degradation of the epoxy matrix resulted in significant deterioration of the transverse tensile strength, F_T^{ut}, as plotted in Figure 10. Specimens exposed to 500 hours of only UV radiation exhibited a 9% decrease in the transverse tensile strength. This decrease in strength was due to the presence of surface microcracks induced by exposure to UV radiation. A decrease of 20% in F_T^{ut} was observed when specimens were exposed to 500 hours of only condensation, which was due to irreversible hydrolysis and plasticization of the epoxy matrix. Specimens exposed to sequential exposure of 1000 hours of UV radiation followed by 1000 hours of condensation exhibited a similar decrease of 21% in the transverse tensile strength. The degradation was most severe for specimens exposed to cyclic UV radiation and condensation. After 1000 hours of cyclic exposure the transverse tensile strength was decrease by 29% as compared to undegraded specimens not exposed to any environment. This deterioration was in accordance with extensive matrix erosion observed for cyclic exposure and *was quite severe considering that the specimens were exposed to a total duration of only 1000 hours!*

Fatigue Testing of Composites Degraded by UV Radiation and Condensation

Fatigue failure is by far the most common type of failure in service loading of structural materials, including composites. The fatigue behavior of composites, however, cannot be described in a way it is applied to metals because the complexity of the internal microstructure of composites introduces a wide range of fatigue damage modes like delamination, matrix cracking, debonding, ply failure and fiber breakage, that normally act in concert with one another to produce a collective result. Further, the fatigue response of a composite laminate will also depend on the properties of each ply and the stacking sequence of those plies. When composites are used in rotating structures such as rotor blades for helicopters and wind turbines fatigue becomes an inherent issue. Apart from high specific strength and stiffness, the fatigue resistance of composites is of utmost importance in these applications, since the loads fluctuate and the structures are generally designed to remain in service for many years. Composite materials usually exhibit a higher fatigue tolerance than metals, and sometimes it becomes time-consuming to fatigue these materials to failure. Most often, they are subjected to cyclic loading until the modulus or the residual strength decreases to a predetermined level. Measurement of residual strength involves destruction of specimen, and hence, reduction in modulus is frequently used as an indication of fatigue damage accumulation after a certain number of cycles, or after certain period in service. Numerous analytical and statistical models that describe fatigue behavior of composite laminates involve modulus values measured during the fatigue test.

Fatigue tests were performed on two sets of IM7/997 $[0/90]_{2S}$ specimens: undegraded and those subjected to cyclic exposure to the environments (condition *D*) (Kumar et al, (2000B)). This particular condition was chosen because it was evident from the results of weight loss, surface morphology and uniaxial tension tests that condition *D* produces the most degradation among all the exposure conditions. For fatigue testing, instead of bonding strain gages, axial clip-on extensometers were used because the accumulation of damage during fatigue testing leads to debonding of strain gages after a few load cycles. As in the case of uniaxial tensile

testing, the ends of the specimens were untabbed. The specimens were held in hydraulic grips with 100-grit sandpaper. The specimens were subjected to uniaxial tension-tension fatigue in load-controlled mode for 100000 cycles on a servo-hydraulic universal testing machine (Instron with 8800 controller) equipped with a 30 kN load-cell. Tests were conducted at three different load levels: 25%, 50% and 75% of the maximum strength of an undegraded, unfatigued $[0/90]_{2S}$ laminate. The loading frequency was kept constant at 5 Hz, and a sinusoidal loading waveform was used. During the testing process, the longitudinal strain and the applied load were recorded on a digital storage oscilloscope.

Figure 11 plots the variation of the elastic modulus, E_x, for undegraded $[0/90]_{2S}$ that was subjected to 50% of the ultimate tensile strength. It can be seen from the plot that the modulus remains fairly constant for the entire duration of fatigue cycling. However, the same trend is not quite observed for a degraded $[0/90]_{2S}$ specimen subjected to 50% of the ultimate tensile strength, as can be seen from Fig. 12. The modulus drops rapidly in the initial few cycles after

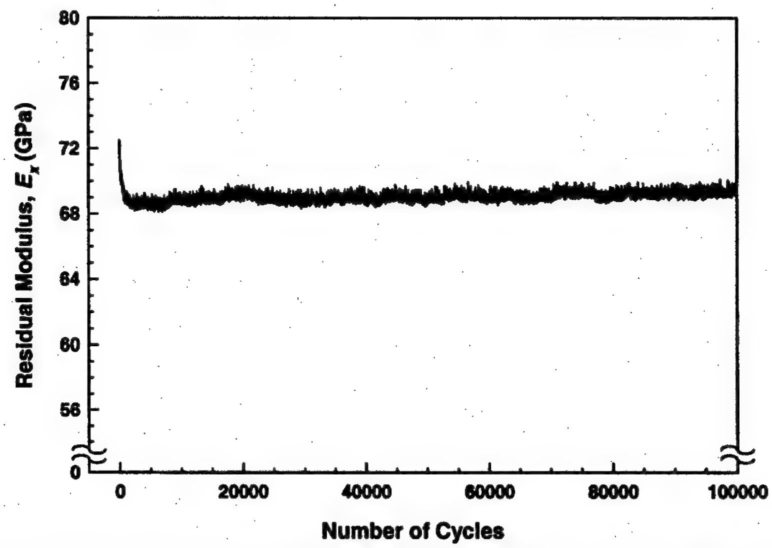

Fig. 11. Modulus reduction in undegraded cross-ply laminate at 50% of UTS

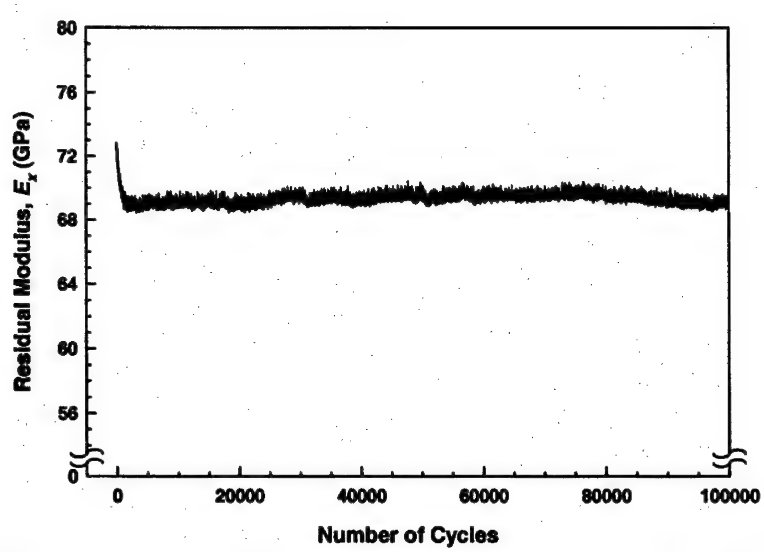

Fig. 12. Modulus reduction in degraded cross-ply laminate at 50% of UTS

which no appreciable changes are observed.

Figure 13 plots the variation of the elastic modulus, E_x, for undegraded $[0/90]_{2S}$ that was subjected to 75% of the ultimate tensile strength. The modulus drops rapidly in the initial few cycles after which it remains fairly constant. The modulus change in this case is very similar to that observed for a degraded $[0/90]_{2S}$ specimen subjected to 50% of the ultimate tensile strength described in the earlier paragraph. However, when a degraded $[0/90]_{2S}$ laminate is fatigued at 75% of the ultimate tensile strength, a marked reduction in the modulus is observed, as shown in Fig. 14. The modulus decreases rapidly at first and then continues decreasing gradually till the end of the experiment.

The decrease in modulus during fatigue loading of composite laminates is attributed to development of microstructural damage long before any visible damage occurs. In a $[0/90]_{2S}$ laminate, the transverse plies show the lowest strength and strain to failure. It is in these plies where damage in the form of transverse cracks first accumulates. The fiber-matrix interface plays an important role in the formation of transverse cracks. In many cases, the interface is weaker

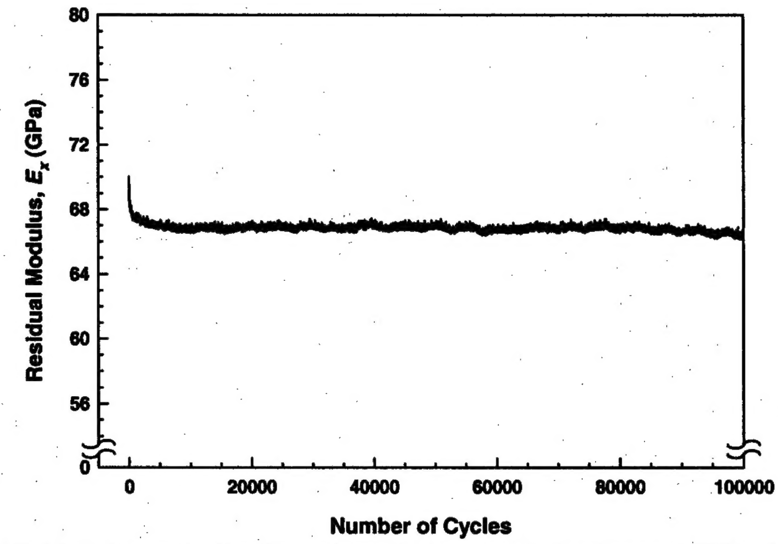

Fig. 13. Modulus reduction in undegraded cross-ply laminate at 75% of UTS

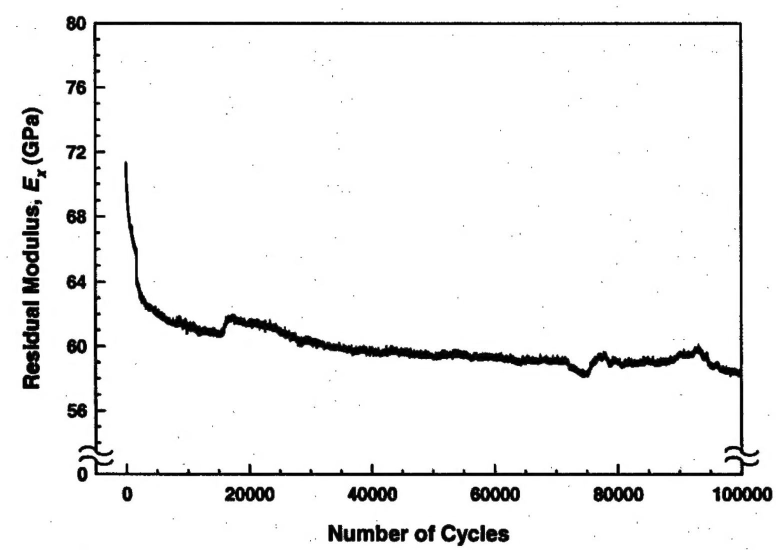

Fig. 14. Modulus reduction in degraded cross-ply laminate at 75% of UTS

than both the fiber and the matrix, meaning that cracking first takes place in the bimaterial interface. The difference in elastic properties promotes crack growth along the interface, both in static and fatigue loading. Eventually, delamination propagating around fibers will coalesce and form macroscopic transverse cracks spanning across the transverse plies. The modulus changes in direct proportion to the number of transverse cracks of a given length that form during fatigue cycling, which itself depends on the applied stress level. This is the reason for a greater reduction in modulus when fatigue loading at 75% than at 50% of the ultimate axial strength for both degraded as well as undegraded laminates.

From the results of uniaxial tensile tests performed on specimens degraded by cyclic exposure to UV radiation and condensation, no changes were observed either in the modulus or the ultimate tensile strength of a $[0/90]_{2S}$ laminate. However, a reduction in the matrix-dominated transverse strength of the unidirectional $[90]_8$ laminate by as much as 29% indicated that the matrix is affected severely during degradation. Further, from the discussion on the physical degradation mechanisms (weight change and surface morphology), it was seen that the degradation is not just restricted to the surface of the specimen, but the synergistic effects produce gradual through-the-thickness damage in the form of extensive matrix erosion and fiber-matrix interface debonding in the transverse plies. In a $[0/90]_{2S}$ specimen, not only the outer surface (which consists of a 0° ply), but also the edges (which contain both 0° as well as 90° plies) are exposed to the degrading environments. In view of the above statements, it is clear that when a degraded specimen is subjected to fatigue loading, an increased number of transverse cracks will develop at the same applied stress level, compared to undegraded specimens. This consequently means that degraded specimens will show more decrease in modulus that undegraded specimens at the same applied stress level.

Collaborative Activities

During the course of this investigation, we have had extensive collaboration with Mr. Joe Morris (Technical Service Manager, Composites) and Mr. Sabah Fattohi (Technical Service Laboratory Manager) at Cytec Engineered Materials, Inc. in Anaheim, California. This collaboration was crucial in the selection of the IM7/997 carbon-epoxy composite as the primary material of interest. This advanced composite is currently under development and qualification for *next- generation* rotorcraft components. Cytec Engineered Materials has graciously donated significant quantities of composite laminates as per our specifications. Furthermore, we have had several fruitful discussions regarding testing parameters and research results.

List of Publications and Reports

Peer-Reviewed Journals and Books

- P. Vaddadi, T. Nakamura, and R. P. Singh (2002), 'Inverse Analysis for Transient Moisture Diffusion through Fiber Reinforced Composites', *Acta materialia*, Vol. 51, pp 177-193.
- B. G. Kumar, R. P. Singh and T. Nakamura (2002), 'Degradation of Carbon Fiber Reinforced Epoxy Composites by Ultraviolet Radiation and Condensation', *Journal of Composite Materials*, Vol. 2713, No. 24, pp. 2713-2733.

Papers Presented at Conferences

- Singh, R. P., Kumar, B. G., and Nakamura, T., "Fatigue Failure in Carbon Fiber Reinforced Epoxy Composites Subjected to Environmental Degradation," Presented at the *Symposium on Damage in Heterogeneous Structures, ASME International Mechanical Engineering Congress and Exposition*, New Orleans, Louisiana, 2002.
- Kumar, B. G., Singh, R. P., and Nakamura, T., "Synergistic Effects of UV Radiation And Condensation On Degradation Of Carbon/Epoxy Composites," Presented at *14th U.S. National Congress of Theoretical and Applied Mechanic*s, Blacksburg, Virginia, 2002.
- Vaddadi, P., Nakamura, T., and Singh, R. P. "Transient Moisture Diffusion Analysis of Fiber Reinforced Composites" Presented at *14 th U.S. National Congress of Theoretical and Applied Mechanic*s, Blacksburg, Virginia, 2002.
- Kumar, B.G., "Degradation of Carbon Fiber Reinforced Epoxy Composites Exposed to Combined UV Radiation and Condensation," *Society of Experimental Mechanics Graduate Student Symposium (Northeast Region)*, Stony Brook, New York, 2002.
- Vaddadi, P., "Analysis of Transient Moisture Absorption in Composites," *Society of Experimental Mechanics Graduate Student Symposium (Northeast Region)*, Stony Brook, New York, 2002. Winner of the Outstanding Paper Award.
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Related articles by other investigators are referenced in the above papers.